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RESEARCH MEMORANDUM

FREE FALL AND EVAPORATION OF n-OCTANE DROPLETS IN THE ATMOSPHERE AS APPLIED TO THE JETTISONING OF AVIATION GASOLINE AT ALTITUDE

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FREE FALL AND EVAPORATION OF n-OCTANE DROPLETS IN THE ATMOSPHERE AS APPLIED TO THE JETTISONING OF AVIATION GASOLINE AT ALTITUDE

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SUMMARY

In connection with proposed rapid jettisoning of aviation gasoline at altitude, a theoretical investigation was made of the free fall and evaporation of n-octane droplets in the atmosphere. n-Octane was selected for study because, on the average, the evaporation characteristics of that substance approximate those of aviation gasoline.

Terminal (equilibrium) falling speeds and Reynolds numbers of such droplets were obtained for altitudes to 11,000 feet over the droplet size range from 6 to 2000 microns. It was concluded that gasoline droplets larger than 2000 microns (0.2 cm) would be unstable and would therefore occur only rarely.

The droplet fall data were used in the calculation of evaporation rates of falling n-octane spheres; decrease of droplet size and change of ambient conditions were taken into account. This procedure was applied in the case of a 2000-micron droplet falling at decreasing speed from 6000 to about 2000 feet through an NACA standard atmosphere (15° C sea-level temperature). The droplet size decreased to about 200 microns during the fall. At that size the falling speed (1.9 ft/sec) was small enough and the evaporation rate great enough to ensure subsequent droplet disappearance at about the 2000-foot level.

Additional calculations were made to determine the magnitudes of pressure effects, temperature effects, and droplet diameter effects. The variation of evaporation rate with pressure for altitudes to 11,000 feet is very small as compared with the variation with temperature and droplet diameter. The evaporation rate increased by a factor greater than 100 as air temperature increased from -37° to +30° C.

It was concluded that use of atomizing devices causing production of droplets less than 200 microns in diameter would make possible gasoline jettisoning without ground contamination at ground clearances in excess of 250 feet at all temperatures above about -37° C. At the highest air temperatures, ground clearances of 1000 feet should suffice even when substantial numbers of the largest (0.2 cm) droplets are

present, that is, when no atomizing devices are used. At the lowest air temperatures, ground clearances as great as thousands of feet will not prevent ground contamination if no atomizing devices are used.

INTRODUCTION

Suggestions have recently been made that a substantial fraction of the fuel load of an airplane should be quickly jettisonable. It has been pointed out that fast jettisoning would greatly reduce crash-fire hazard and would substantially increase the lift-drag ratio in the case of operation under the condition of failure of one or more engines.

2830

One obvious means of achieving this goal would be the use of disposable tanks. It is clear, however, that the dropping of fuel-laden tanks might not be desirable in many instances. The only practicable alternative would appear to be a rapid discharge of the fuel at altitude.

In general, it is desirable that no significant amount of discharged fuel reach any ground installation. The only mechanisms which could conceivably lead to dispersal at altitude are evaporation and/or break-up into minute droplets ("atomization") which would remain suspended indefinitely.

The subject of atomization is a very complex one around which an extensive literature has accreted. It is assumed here only that in some manner, as by the breaking-up of a jet, the fuel has been ejected into the atmosphere and is present in the form of droplets of varying sizes.

The present investigation was conducted at the NACA Lewis laboratory with the chief purpose of furnishing preliminary estimates of the fractions of original masses of droplets of gasoline which will still be present after such droplets have fallen through various distances under different conditions. It is assumed that n-octane evaporation calculations will apply to gasoline. While no estimates are made herein of the original distribution of droplet sizes, a brief discussion of the maximum stable size and of the motional dynamics of falling gasoline droplets is presented in the section MAXIMUM DROPLET SIZE AND DROPLET MOTION. A knowledge of droplet speeds is clearly required in the calculation of evaporation rates. An explanation is then presented of the rather elementary techniques which were employed to obtain the local rates of evaporation and the total mass losses. Finally, the results of the calculations are presented and discussed.

All symbols used in the report are listed and defined in the appendix.

2820

CT-1 back

MAXIMUM DROPLET SIZE AND DROPLET MOTION

Irrespective of the original mechanism of droplet formation, it is intuitively clear that the largest stable droplet during free fall through the atmosphere will be that one for which the surface tensile forces are just sufficient to overcome the disruptive forces. The latter ordinarily consist of the drag shear and normal-pressure forces, although centrifugal forces may also be present (ref. 1). Shearing forces may be ignored only in situations characterized by high Reynolds numbers of gas-stream flow with respect to the droplet and by rather large droplet fluid viscosity (ref. 2).

Nevertheless, while there are certain contradictions in the literature, it is evident that some dimensionless parameter which is essentially a measure of the ratio of surface forces to deformation-resisting forces will determine the maximum stable droplet size under given conditions. Such a parameter is, for example, the dimensionless Weber number defined by the equation

$$We = \frac{\rho_a U^2 R'^2}{\alpha R'} = \frac{\rho_a U^2 R'}{\alpha} \qquad (1)$$

The effects of tangential forces (shear stresses) cannot be ignored at Reynolds numbers below 1000 (ref. 2). It follows that an unknown function providing shearing-force information should be added to the numerator of equation (1); this fact in no way affects the dependence of the resulting modified Weber number on the surface tension.

The following table, excerpted from reference 2, lists values of maximum droplet radius, corresponding free-fall (terminal) droplet speeds in normal air, free-fall Reynolds numbers, surface-tension values, and values of the ratio (surface tension)/(critical radius) for several substances:

Liquid	R'_c,	U_c, ft/sec	Re_c	α, dyne/cm	α/R'_c, dyne/sq cm
Distilled water	0.50	40.02	16,300	70.6[a]	141.2
Carbon tetrachloride	.18	30.35	4,400	24.5	136.1
Methyl salicylate	.325	37.07	9,800	34.3	105.5
Glycerine plus 20 percent water	.45	41.83	15,300	63.7	141.5

[a]Probably too low.

The approximate constancy of the ratio α/R_c' is apparent; the average of the four ratios is 131.

In the case of gasoline, the surface tension is about 21 dynes per centimeter (ref. 3). If 131 dynes per square centimeter is accepted as a working value, the resulting maximum possible gasoline droplet radius is 0.16 centimeter. It is further noted, however, that such a radius is rather improbable, as is a water droplet of 0.5-centimeter radius. Accordingly, in this report a gasoline droplet diameter of 0.2 centimeter has been arbitrarily selected as representative of the limiting size of probably occurring droplets. On the other hand, it should be noted that droplets having diameters of the order of 0.3 centimeter will occasionally appear; these will be very unstable.

2830

Equality of drag force and object weight will determine the terminal (equilibrium) falling speed of any object. In the case of a (rigid) sphere, the following relation applies:

$$\frac{4}{3}\pi\rho_d\, gR'^3 = C_D\pi R'^2\,\frac{\rho_a\, U_t^2}{2} \tag{2}$$

This may be converted into the following:

$$\frac{32}{3}\,\frac{\rho_d\,\rho_a\, gR'^3}{\mu_a^2} = C_D\,\frac{4\rho_a^2\, R'^2 U_t^2}{\mu_a^2} = C_D\, Re_t^2; \tag{3}$$

A definition of φ appears in reference 4 as

$$\varphi \equiv \frac{32}{3}\,\frac{\rho_d\,\rho_a\, gR'^3}{\mu_a^2}$$

and is therein presented as a function of Re_t (see fig. 4 of ref. 4), which may be done since $C_D Re_t$ is a unique function of Re_t provided the transonic region is not entered.

Since φ may be calculated for a given radius once the properties of the sphere and the ambient medium are known, the terminal Reynolds numbers and speeds are easily obtained.

The density of 115/145 aviation gasoline may be taken, with negligible error, as 0.700 gram per cubic centimeter (ref. 5).

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The following table exhibits the results of such terminal motion calculations for altitudes of 1000, 6000, and 11,000 feet; NACA standard atmosphere temperatures and pressures were used:

		Altitude, ft					
		1000 (t_a = 55.4° F)		6000 (t_a = 37.6° F)		11,000 (t_a = 19.8° F)	
r', cm	$D_{d,\mu}$, micron	Re_t	U_t, ft/sec	Re_t	U_t, ft/sec	Re_t	U_t, ft/sec
0.1	2000	730	17.41	700	19.05	660	20.47
0.03162	632.4	90.0	6.788	82.5	7.100	78.0	7.648
0.01	200	7.70	1.837	7.0	1.905	6.40	1.985
0.003162	63.24	0.3838[a]	0.2894	0.342[a]	0.2943	0.3073[a]	0.3013
0.001	20	0.01214	0.02894	0.01082	0.02944	0.00971	0.03011
0.0003162	6.324	0.0003838	0.002894	0.0003421	0.002943	0.0003073	0.003013

[a]For the smaller speeds, Stokes' Law ($C_D = 24/Re_t$) was used, which is equivalent to $Re_t = \varphi/24$.

These results are also exhibited in figure 1, in which it is clearly shown that neither terminal Reynolds numbers nor terminal speeds vary greatly with altitude within the range covered by the calculations.

If a droplet is evaporating, the terminal speed and Reynolds number, in general, will be constantly decreasing. (An exception to this will occur, for example, when a large, slowly evaporating droplet falls so rapidly that the increase in air density with approach to the ground more than offsets the diametral change.) The question therefore arises as to the validity of the assumption that the instantaneous motion is virtually what it would have been under precisely steady-state conditions, that is, in the absence of evaporative change (or air-density change). The behavior of water droplets under various conditions is presented in reference 5, where it is shown that the distances required to ensure attainment of equilibrium motion conditions are of the order of a few feet for the largest droplets under the most severe acceleration or deceleration conditions. In none of these cases is the "relaxation" distance greater than 40 feet; it is generally less than 25 feet for droplets smaller than 0.2 centimeter in diameter. Accordingly, in this study it was assumed that gasoline droplet terminal conditions prevailed throughout droplet histories provided the droplets were dispersed sufficiently to ensure absence of aerodynamic interaction among them. Since vertical dispersion will occur in any event as a result of the large variation of falling speed with diameter, it would appear reasonable to neglect such interactions; this procedure will be invalid during the initial dispersion period immediately subsequent to the

jettisoning. This initial period will be of doubtful duration, but will be brief compared with the total period of droplet evaporation. In any case, the assumption of absence of entrainment phenomena is made throughout this study.

EVAPORATION CALCULATIONS

The rate of evaporation (mass loss per unit surface area per unit time) is equal to the product of two variables, namely, the mass-transfer coefficient and the difference in vapor pressure between droplet and ambient atmosphere. The droplet vapor pressure is a unique function of surface temperature, while the ambient vapor pressure may be taken as essentially zero in the atmosphere (except possibly during the initial dispersion period).

2830

The droplet temperature will depend, as in the case of the common wet-bulb psychrometer, on the location on the droplet temperature scale of the balance point between sensible heat transferred to the droplet by conduction and convection from the atmosphere and heat removed from the droplet, principally by the evaporating fluid.

The heat- and mass-transfer coefficients depend on the droplet size and on the instantaneous relative air-mass flow rate, that is, the droplet falling speed and local air density. Since periods of free fall in the atmosphere are long compared with the rates at which successive equilibrium states are attained under various conditions, it is permissible to assume that the droplet is, at every point, essentially in psychrometric equilibrium with the local environment.

Most of the calculations of local mass-loss rates were carried out on a step basis. In outline form, the procedure was as follows:

The initial falling speed and Reynolds number having been determined for the starting altitude (6000 feet; NACA standard atmosphere) and assumed droplet size (0.2 cm), the initial heat- and mass-transfer coefficients were computed. In turn, the droplet temperature, vapor pressure, and mass-loss rate were computed. The necessary relations are subsequently given.

The duration of the first step was then taken as that period during which a fixed, predetermined fractional mass loss (0.10875) occurred. The fractional loss was based on the mass existing at the end of the preceding step, rather than on the original mass. Therefore, each successive mass was 0.89125 of the preceding mass.

2830

The diameters and masses of the successive steps were thus established in advance. The curves of figure 1 reveal that falling speeds and Reynolds numbers are nearly independent of altitude within the altitude range studied. It was therefore possible to establish beforehand a list of terminal speeds and Reynolds numbers corresponding to the successive drop sizes for the starting altitude. The diameters used in the calculations were values more nearly representative of average conditions existing over the successive intervals than either the respective initial or final values would have been. The mean mass was taken as 0.945625 of the starting mass at each step ($0.945625 = 1 - 0.10875/2$). The mean diameter was then taken as $0.945625^{\frac{1}{3}}$ or 0.981534 of the starting diameter. (If the mean diameter is defined by the relation $\overline{D_{d,i}}^{-2} = 0.5(D_{d,i}^{-2} + D_{d,i+1}^{-2})$, where $\overline{D_{d,i}}$ is the mean diameter over the i^{th} step and $D_{d,i}$ and $D_{d,i+1}$ are the respective initial and final diameters, the mean diameter so obtained is also about 0.981.)

Once the period of fall and mean speed had been determined, the loss of altitude for the first step was then available. A more nearly exact mean temperature and pressure for that step were than obtained from reference 6; the step calculations were then repeated. After the conditions at the end of the first step had been calculated, the distance of fall for the second step was estimated, the average temperature and pressure were obtained, and the procedure of the first step repeated. The entire cycle was reiterated until the desired droplet size was reached.

The relations used were the following:

Heat-balance or psychrometric equation:

$$t_a - t_d = \frac{\lambda_d h_m}{h_h} (p_d - p_a) \tag{4}$$

It has been shown by many investigators (ref. 7, for example) that this relation is valid provided that no substantial amount of sensible heat is transferred by the liquid vapor. This will be true, in general, when both the mass- and heat-transfer rates are low. Further, if this is the case, the mass- and heat-transfer rates will be essentially independent.

Under such conditions, mass-transfer and heat-transfer Nusselt numbers may be defined (refs. 4 and 7) as follows:

$$\left.\begin{aligned} Nu_m &\equiv \frac{h_m R_d T D_d}{\beta} \\ Nu_h &\equiv \frac{h_h D_d}{k_h} \end{aligned}\right\} \qquad (5)$$

For most pairs of gases, the diffusion coefficient β varies with temperature and pressure in the following manner (ref. 8):

$$\beta = \beta_o \left(\frac{T_a}{N.T.}\right)^2 \left(\frac{N.P.}{P_a}\right) \qquad (6)$$

The question arises as to the constancy of β_o and of other liquid or gas properties during an evaporation process.

In the case of gasoline, a complex mixture of many compounds, a fractional distillation process, in effect, takes place as evaporation proceeds. Accordingly, such properties as the air-gasoline vapor diffusion coefficient, heat of vaporization, and so forth will vary markedly with time.

A rather radical solution of the difficulty consists in replacing, on paper, the gasoline droplet by a droplet of liquid which, on the average, exhibits roughly the same evaporative behavior as gasoline. The term "evaporative behavior" refers here only to the rate of loss of mass and not, for example, to the properties of any of the successive fractions evaporated. The selection of n-octane as a representative single material should yield evaporation data reasonably similar to those for gasoline. The correspondence will not be close during the initial evaporation period. At that time, the higher fractions, which have vapor pressures a number of times as high as that of n-octane, will evaporate at a high rate. Further, after most of the original gasoline has been vaporized, the converse will be true; the evaporation rate of the residual liquid will be lower than that of n-octane.

Nevertheless, the results of calculations based on the properties of n-octane are believed to be approximately correct for a mixture including substantial quantities of n-octane, isooctane, heptanes, and other paraffins. Accordingly, the value of β_o cited in reference 8 for n-octane was used, namely, 0.0505 square centimeter per second.

2830

The following additional constants were used in the calculations; the value of the Schmidt number Sc_d is discussed subsequently:

Constant	Magnitude	Units	Source
Thermal conductivity of air, $k_{h,o}$	2422	erg/cm	Reference 9
Molecular weight of air, M_a	28.966	gm/mole	Reference 10
Molecular weight of n-octane, M_d	114.224	gm/mole	Reference 11
Universal gas constant, R	8.3144×10^7	erg/°K	Reference 11
Schmidt number for n-octane (in air), $Sc_{d,o}$	2.618		
Heat of vaporization of n-octane, $\lambda_{d,o}$	$3.73_4 \times 10^9$	erg/gm	Reference 12 data on vapor pressure and extended plot of heat of vaporization data in reference 13.

The following substitutions are now made in equation (4): (1) h_m and h_h are replaced by their equivalents as obtained by solving equation (5); (2) β is replaced in the expression for h_m by relation (6); (3) k_h is replaced in the expression for h_h by $k_h = k_{h,e}(T_a/N.T.)^{0.85}$; and (4) λ_d is replaced in the final expression by $\lambda_d = \lambda_{d,e}(\lambda_d/\lambda_{d,e})$.

The resulting expression is the following:

$$t_a - t_d = \lambda_{d,o}\left(\frac{Nu_m}{Nu_h}\right)\left(\frac{N.P.}{P_a}\right)\left(\frac{T_a}{N.T.}\right)^{0.15}\left(\frac{\lambda_d}{\lambda_{d,o}}\right)\frac{\beta_o M_d}{(N.T.)k_{h,o} R}(p_d - p_a)$$

$$= 0.3915 \times 10^{-3}\left(\frac{Nu_m}{Nu_h}\right)\left(\frac{N.P.}{P_a}\right)\left(\frac{T_a}{N.T.}\right)^{0.15}\left(\frac{\lambda_d}{\lambda_{d,o}}\right)(p_d - p_a) \qquad (7)$$

In equation (7), the temperature difference is given in degrees centigrade, while the vapor pressure difference is given in dynes per square centimeter. The vapor pressure is generally given in millimeters of mercury in the literature; if p^* is used to represent a vapor pressure so expressed, equation (7) becomes the working form of the psychrometric equation for n-octane under moderate temperature and pressure conditions:

$$t_a - t_d = 0.522 \left(\frac{Nu_m}{Nu_h}\right)\left(\frac{N.P.}{P_a}\right)\left(\frac{T_a}{N.T.}\right)^{0.15}\left(\frac{\lambda}{\lambda_{d,o}}\right)(p_d^* - p_a^*) \qquad (8)$$

This states that, at low relative flow rates, the temperature drop at normal pressure of an n-octane sphere is roughly half the difference in vapor pressure existing between the sphere surface and the atmosphere, when the latter is expressed in millimeters of mercury. In most cases, p_a^* will be virtually zero. The reason for the restriction of the observation to low relative flow rates lies in the variation of the ratio Nu_m/Nu_h, which can only be experimentally determined.

2830

The following expressions have been obtained from data cited in reference 4 by a trial-and-error fitting process; it is not contended that these are the "best" expressions possible, but only that they fit the data fairly well for moderate (<1000) Reynolds numbers:

$$\left.\begin{aligned} Nu_m &= 2 + 0.39\ Sc^{\frac{1}{3}}\ Re^{0.56} \\ Nu_h &= 2 + 0.246\ Pr^{\frac{1}{3}}\ Re^{0.6393} \end{aligned}\right\} \qquad (9)$$

These expressions are represented graphically in figure 2, while their ratio Nu_m/Nu_h is presented in figure 3. Fourth nonzero figures are not of significance here; third significant figures may be erroneous by several units. The values plotted, however, were those used in the calculations.

The value 0.73 was adopted as the Prandtl number for pure air. The Schmidt number is given in reference 7 as 2.58 at 25° C; this value agrees with a value calculated on the basis of a diffusion coefficient of 0.060 at 25° C, which is the value cited in the same reference. In turn, the value $\beta = 0.060$ agrees well with the value obtained by using equation (6) and β_o, namely, 0.0601_6. If the latter is used, the Schmidt number at 25° C is found to be 2.57. Finally, the Schmidt number, which varies very slowly with temperature, was 2.618 at 0° C for n-octane, when $\beta_o = 0.0505$ and the relation $Sc_d = \mu_a/P_a\beta$ are used.

Vapor pressure was plotted against heat of evaporation (fig. 4) to facilitate trial-and-error solutions of equation (8). In the original figure, the temperature could be read to a tenth of a degree and the vapor pressure to at least 1 percent.

As a check on the validity of relations (8) and (9), they were used to calculate wet-bulb temperatures of n-octane spheres at three air temperatures. The results for a Reynolds number of 1000 are compared in

figure 5 with experimental data from reference 14 obtained at about the same Reynolds number. The agreement is to some extent fortuitous, but it is clear that, at least under roughly normal ambient conditions, the theoretical heat- and mass-transfer rates calculated from the relations given here will be substantially correct (for n-octane).

The mean fractional evaporation rate at the i^{th} step (designated $\overline{\Lambda_i}$, g/(g)(sec)) was calculated as follows; note the assumption in equation (10) that the partial n-octane vapor pressure in the atmosphere is negligible:

2830

$$\overline{Q_{m,i}} = \overline{h_{m,i}}\ \overline{A_{d,i}}\ \overline{p_{d,i}} \tag{10}$$

$$= \pi\ \overline{D_{d,i}}^2\ \overline{h_{m,i}}\ \overline{p_{d,i}}$$

CT-2 back

It therefore follows that

$$\overline{\Lambda_i} = \frac{\pi\ \overline{D_{d,i}}^2\ \overline{h_{m,i}}\ \overline{p_{d,i}}}{(\pi/6)\ \rho_d\ \overline{D_{d,i}}^3}$$

$$= \frac{6\ \overline{h_{m,i}}\ \overline{p_{d,i}}}{\rho_d\ \overline{D_{d,i}}}$$

The following substitutions and changes are now made:

$$\overline{p_{d,i}} = 1333.2\ \overline{p^*_{d,i}};$$

$$\overline{D_{d,i}} = \overline{D_{d,\mu,i}} \times 10^{-4};$$

$$\rho_d = 0.700$$

$$h_m = \frac{Nu_m}{D_d}\ \beta\ \frac{M_d}{RT_a}$$

$$= \frac{Nu_m}{D_d}\ \beta_o \left(\frac{T_a}{N.T.}\right)^2 \left(\frac{N.P.}{P_a}\right)^2 \frac{M_d}{RT_a}$$

2830

or

$$\overline{h_{m,i}} = \frac{\overline{Nu_{m,i}}}{\overline{D_{d,\mu,1}}} \frac{\beta_o}{(N.T.)R_d} \left(\frac{\overline{T_{a,i}}}{N.T.}\right) \left(\frac{\overline{N.P.}}{\overline{P_{a,i}}}\right)^2 \times 10^4 \tag{11}$$

The fractional mass loss rate then becomes

$$\overline{\Lambda_i} = \left(\frac{6 \times 1333.2 \times 10^8 \times 0.0505}{0.700 \times 273.2 \times 0.7279 \times 10^6}\right) \frac{\overline{Nu_{m,i}}}{\overline{D_{d,\mu,i}}^2} \left(\frac{\overline{T_{a,i}}}{N.T.}\right) \left(\frac{N.P.}{\overline{P_{a,i}}}\right)^2 \overline{p_{d,i}^*}$$

or

$$\overline{\Lambda_i} = 2.90 \times 10^2 \frac{\overline{Nu_{m,i}}}{\overline{D_{d,\mu,i}}^2} \left(\frac{T_{a,i}}{N.T.}\right) \left(\frac{N.P.}{\overline{P_{a,i}}}\right)^2 \overline{p_{d,i}^*} \tag{12}$$

The number of seconds required for a fractional loss of 0.10875 of the mass present at the beginning of a step is then

$$\Delta_i\theta = \frac{0.10875}{\overline{\Lambda_i}} \tag{13}$$

The distance traveled during the i^{th} step is the product of $\Delta_i\theta$ and $U_{t,i}$; the total distance fallen and the existing altitude are then obtainable in an obvious manner.

RESULTS AND DISCUSSION

The original intention had been to have complete sets of calculations performed for the fall of droplets of several sizes from several altitudes at several temperatures. The achievement of a reasonable degree of accuracy in the calculations required, however, computations somewhat lengthier than at first thought necessary, and the program was therefore abridged.

Calculations for the case of a droplet having an initial diameter of 2000 microns and falling through a standard atmosphere from 6000 feet have been carried sufficiently far at this time to make possible predictions concerning the release of gasoline from the altitude in question.

The mass of the droplet as a function of altitude is shown in figure 6; the respective diameters are given at relative droplet mass values of 1, 0.1, 0.01, and 0.001. Only the results of calculations at each fifth step have been plotted.

It is clear that large droplets of n-octane (and, therefore, probably of gasoline) will fall large distances (at least 4000 ft) under normal atmospheric conditions before their sizes are reduced to values such that the droplets will have essentially come to rest. It is to be noted (fig. 1) that gasoline droplets (or n-octane droplets having about the same density) of 200 microns diameter will fall freely (at 6000 ft) at a speed of 1.9 feet per second. It is safe to assume that such droplets will not reach the ground unless air temperatures are extremely low; it is estimated that a 200-micron droplet will lose 11 percent of its mass while falling 54 feet at -37° C ($\cong -35^{\circ}$ F).

2830

Figure 6 may be used to determine residual masses of smaller droplets falling from the altitudes indicated along the abscissa scale. For example, at 4696 feet the residual mass of the original droplet is 0.5623 of the original mass (which was 2.932×10^{-3} g); at 2972 feet the residual mass of the original droplet is 0.1000 of the original mass. Further, the respective diameters at the two altitudes mentioned are 1651 microns and 928 microns. It is clear, considering the assumptions which underlie the calculations, that the residual mass of a 1651-micron droplet falling from 4696 feet to 2972 feet (in normal atmosphere) will be 0.1000/0.5623 of the original mass, or 0.1778 of the original mass.

The first of the following tables exhibits in abridged form the respective masses, diameters, and so forth, for the set of calculations in question; the second table exhibits the masses, diameters, and so forth, for a small number of calculations which were made in lieu of additional complete sets of calculations to determine the effects of initial diameter variation at a fixed altitude, temperature variation at a fixed pressure altitude, and altitude variation at a fixed temperature:

Step number	M_1/M_1	$D_{d,\mu,i}$ and $\overline{D_{d,\mu,i}}$, microns	$\overline{Re_{t,i}}$	$\overline{U_{t,i}}$, ft/sec	$\overline{t_a}$, °C	$\overline{t_d}$, °C	Λ_i, g/(g)(sec)	$\Delta_i\theta$, sec	Altitude, ft
	1.0000	2000							6000
1		1963	670	18.9	3.43	0.67	0.00653	16.65	
	.5623	1651							4696
6		1620	478	16.2	5.89	2.79	.00901	12.07	
	.3162	1363							3869
11		1337	340	13.9	7.46	4.13	.01194	9.11	
	.1778	1125							3330
16		1104	237	11.8	8.49	4.99	.01530	7.11	
	.10000	928.3							2972
21		911.1	167	10.0	9.17	5.54	.01962	5.54	
	.05623	766.2							2734
26		752.1	115	8.41	9.63	5.94	.0247	4.41	
	.03162	632.5							2576
31		620.8	79.8	7.00	9.92	6.20	.0314	3.47	
	.01778	522.0							2472
36		512.4	54.0	5.81	10.12	6.40	.0394	2.76	
	.01000	430.9							2405
41		422.9	36.4	4.73	10.25	6.54	.0503	2.16	
	.00562	355.7							2362
46		349.1	24.3	3.82	10.33	6.68	.0640	1.70	
	.00316	293.6							2335
51		288.1	16.2	3.05	10.38	6.79	.0826	1.32	
	.00178	242.3							2319
56		247.1	11.4	2.52	-----	----	------	-----	

Note: Values given on line above that on which step number is entered are those applying to conditions at the beginning of step. Values on step line are average values.

Diameter effects								
Altitude, ft	$\overline{D_{d,\mu}}$, microns	$\overline{Re_t}$	$\overline{U_t}$, ft/sec	t_a, °C	t_d, °C	Λ, g/(g)(sec)	$\Delta\theta$, sec	ΔH, ft
6000	1963	670	18.9	3.11	0.39	0.00642	16.94	320
	911.1	167	10.0		.28	.01500	7.25	72.5
	422.9	36.4	4.73		.26	.0376	2.89	13.68
	196.3	6.62	1.84		.54	.1044	1.042	1.917
	91.11	.940	.554		.81	.345	.315	.1746
	42.29	.107	.137		.99	1.402	.0776	.0108
Temperature effects								
6000	1963	670	18.9	-37.00	-37.12	0.000226	481	9100
				-12.00	-13.10	.00246	44.3	837
				3.11	.39	.00642	16.94	320
				13.00	8.30	.01151	9.45	178.6
				30.00	21.0	.0234	4.66	88.0
Altitude effects								
1000	1963	710	17.1	13.00	8.99	0.01011	10.76	184.0
6000		670	18.9		8.30	.01151	9.45	178.6
11,000		638	20.0		7.74	.01251	8.69	173.9

The droplet diameters used were average values corresponding to selected steps of the step-calculations. On the other hand, the pressures used were those of the NACA standard atmosphere at the indicated altitudes rather than the mean values over an initial step.

In the previous table, selected results are given for the case of a 2000-micron droplet falling through an atmosphere, the characteristics of which change with altitude. The "Diameter effects" group of the second table exhibits differences, to the contrary, caused solely by diameter changes. A detailed comparison with the original step calculations for the extended-fall case indicates that the higher evaporation rates of that situation may easily be accounted for on the basis of the higher air temperatures existing at the lower altitudes. For example, in the step calculations (previous table), the number of seconds required for the standard 11-percent mass loss to occur at step number 21 is 5.54 (at a mean altitude of 2940 ft). In the present case, the number of seconds required for a droplet of the same diameter (911.1 microns) to lose that much mass is 7.25. The respective droplet temperatures are 5.54° C (a coincidental repetition of the same number) and 0.28° C. The wet-bulb depression is roughly the same for both cases, namely, some 5° or 6° C, while the ratio of the two evaporation rates is roughly proportional to the ratio of the two vapor pressures. Such reasoning will facilitate the estimation of evaporation rates under varying conditions; temperature and diameter effects may be combined in estimating loss rate for a particular droplet size at a particular temperature.

2830

The very great variation of evaporation rate with temperature is indicated in the second group of this table. The distance of fall at -37° C is so large that the assumption of constancy of temperature is, of course, not tenable; it is clear, however, that under severe conditions reliance may not be placed on evaporation as a dispersing mechanism. On the other hand, the loss rates at high temperatures are such that moderately low-altitude jettisoning even without the use of finely atomized sprays would be feasible, since the largest droplets (2000 microns) can drop, at most, perhaps 1000 feet before essentially coming to rest. (This estimate is based in part on the 4000-ft drop previously found for the case of a 2000-micron droplet falling through an NACA atmosphere.)

The evaporation figures of the "Altitude effects" group show quite clearly the rather small effects of pressure differences over the indicated altitude range.

CONCLUSIONS

A theoretical investigation was made of the free fall and evaporation of n-octane droplets in the atmosphere. On the basis of the analysis and numerical results the following conclusions were drawn; these conclusions will be approximately applicable to the fall of aviation gasoline:

1. As the droplets evaporate, their masses, diameters, and therefore their falling speeds decrease. Motion and evaporation analyses are therefore most easily made on a step basis, with changes of pressure and temperature with altitude taken into account; droplet characteristics and environmental conditions are supposed constant during each step.

2. Droplets having diameters greater than 0.3 centimeter will either not be formed or, having been formed, will break up immediately into smaller droplets. The largest stable droplets will have diameters of the order of 0.2 centimeter.

3. Temperature effects (at a given droplet diameter) on evaporation rates, and therefore on total distances of fall, are far more important than pressure or motion effects. The rate of evaporation increases by a factor of more than 100 over the air-temperature range -37° C ($\cong -35^{\circ}$ F) to $+30^{\circ}$ C (86° F).

4. A droplet having a diameter of 200 microns (0.02 cm) or less will fall at a speed of less than 2 feet per second at altitudes below 11,000 feet. The rate of evaporation, and therefore of decrease of size and falling speed, of any such droplet will be great enough even at air temperatures as low as -37° C to ensure that the droplet will not reach ground level when ground clearance exceeds about 250 feet. It follows that ground contamination will not occur, irrespective of air temperature, if nearly all of the jettisoned fuel has been atomized, that is, if the fuel is present in the form of droplets less than 200 microns in diameter at ground clearances in excess of 250 feet.

5. Large droplets will fall long distances through air under normal or near-normal conditions. For example, in an NACA standard atmosphere (15° C sea-level temperature), a droplet having a diameter of 2000 microns (0.2 cm) at 6000 feet will fall while evaporating at decreasing speed to about 2000 feet. At this level it would have a diameter of less than 200 microns and would remain approximately at this level while evaporating completely.

6. At the highest air temperatures (about 30° C), ground clearances of 1000 feet will probably be sufficient to avoid ground contamination by falling droplets, irrespective of the original distribution of droplet sizes. At the highest air temperatures, therefore, the use of finely atomizing spray devices will be unnecessary.

7. At the lowest air temperatures (below about -20° C), only the use of finely atomizing spray devices will prevent ground contamination even if ground clearances are of the order of thousands of feet.

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2830

APPENDIX - SYMBOLS

A	surface area, sq cm
C_D	drag coefficient for a sphere
D	diameter, cm
g	gravitational constant, dyne/g
H	altitude, cm (except where explicitly expressed in ft)
h_h	heat-transfer coefficient, erg/(sq cm)(sec)(^oC)
h_m	mass-transfer coefficient, (g/(sec)(sq cm))/(dyne/sq cm)
k_h	thermal conductivity of ambient gas, erg/(cm)(sec)(^oC)
M	molecular weight, g/mole
Nu	Nusselt number
N.P.	1 atmosphere, dyne/sq cm (1,013,250)
N.T.	reference temperature, ^oK (273.2)
P	ambient pressure, dyne/sq cm
Pr	Prandtl number
p_a	partial pressure of evaporating-liquid vapor in ambient gas, dyne/sq cm
p_d	saturation vapor pressure of evaporating liquid at sphere temperature, dyne/sq cm
Q_m	rate of mass loss from sphere, g/sec
R	universal gas constant, erg/(^oK)(mole)
R_d	gas constant of evaporating liquid, erg/(^oK)(g)
Re	relative droplet-air Reynolds number
r	droplet radius, cm
Sc	Schmidt number, $\mu_a/\rho_a\beta$
T	absolute temperature, ^oK

2830 CT-3

t	temperature, ^{o}C (except where explicitly expressed in ^{o}F)
U	relative air-droplet speed, cm/sec (except where explicitly expressed in ft/sec)
We	Weber number defined by equation (1)
α	surface tension, dyne/cm
β	diffusion coefficient, sq cm/sec
Λ	fractional mass-loss rate, g/(g)(sec)
λ	heat of vaporization, erg/g
μ	viscosity, poise
ρ	density, g/cu cm
φ	free-fall parameter defined by relation following equation (3)

Subscripts:

a	ambient gas
c	critical value (referring to value above or beyond which droplet tends to break up)
d	evaporating liquid
h	heat transfer
i	step number designation
m	mass transfer
o	reference conditions (N.P., N.T.) (Note that these are not identical with NACA standard atmosphere sea-level conditions. In the latter case, the air temperature is taken as 15^{o} C.)
t	terminal (equilibrium) state
μ	dimensions microns instead of cm

The bar $(-)$ denotes mean value over a step (calculation interval).

Superscripts:

*	dimensions mm Hg instead of dyne/sq cm

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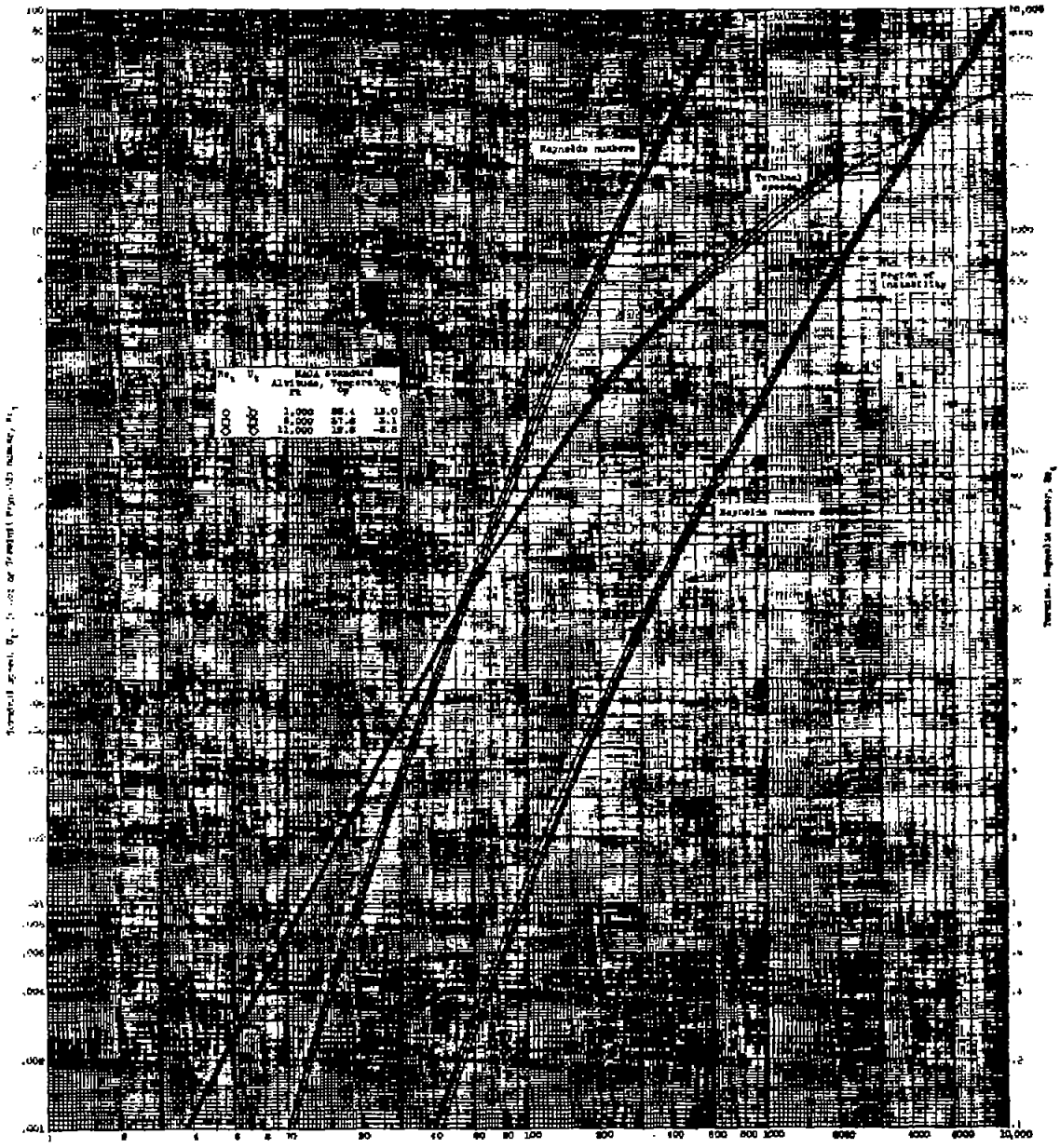

Figure 1. - Terminal motion characteristics of gasoline droplets.

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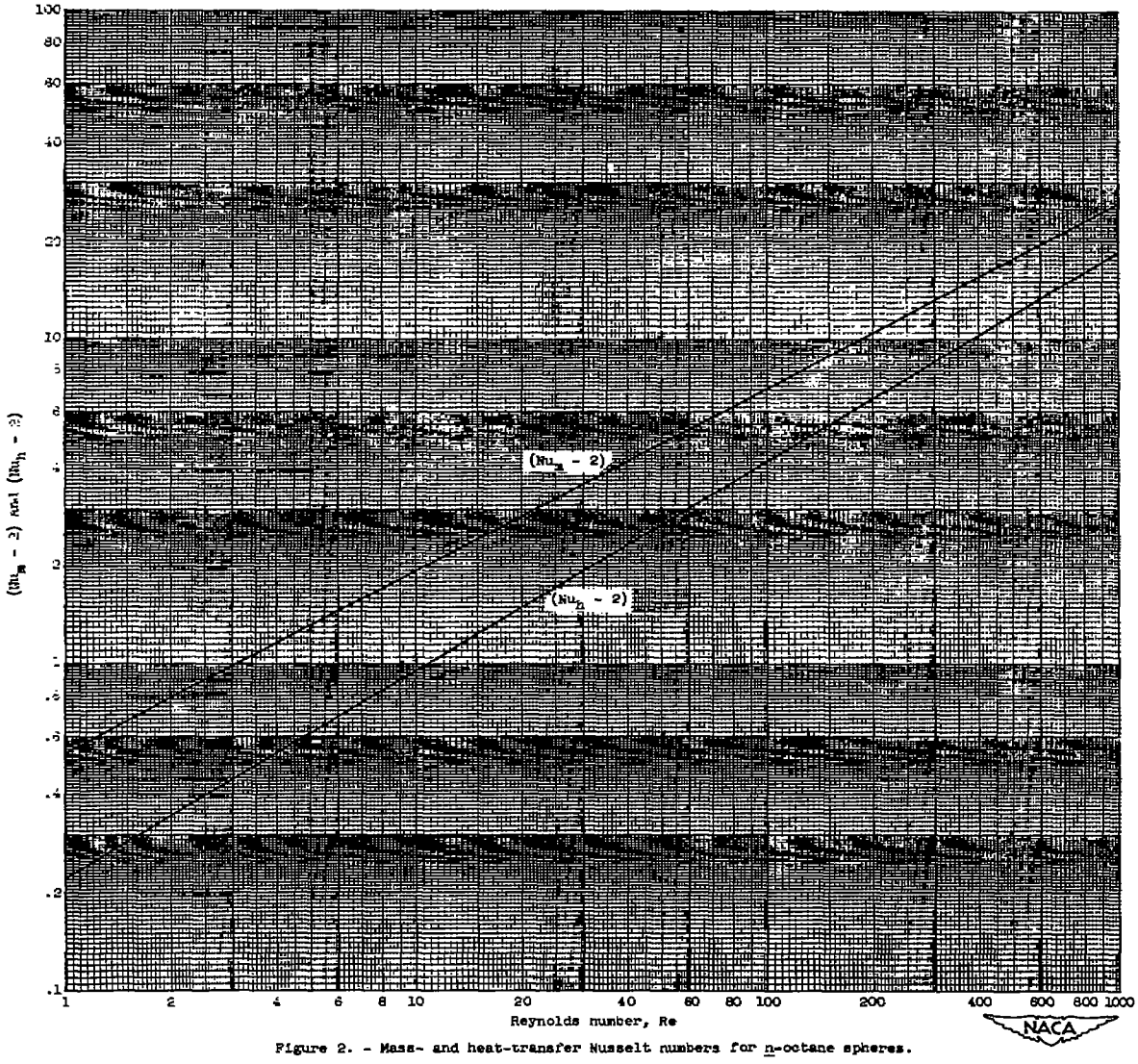

Figure 2. - Mass- and heat-transfer Nusselt numbers for n-octane spheres.

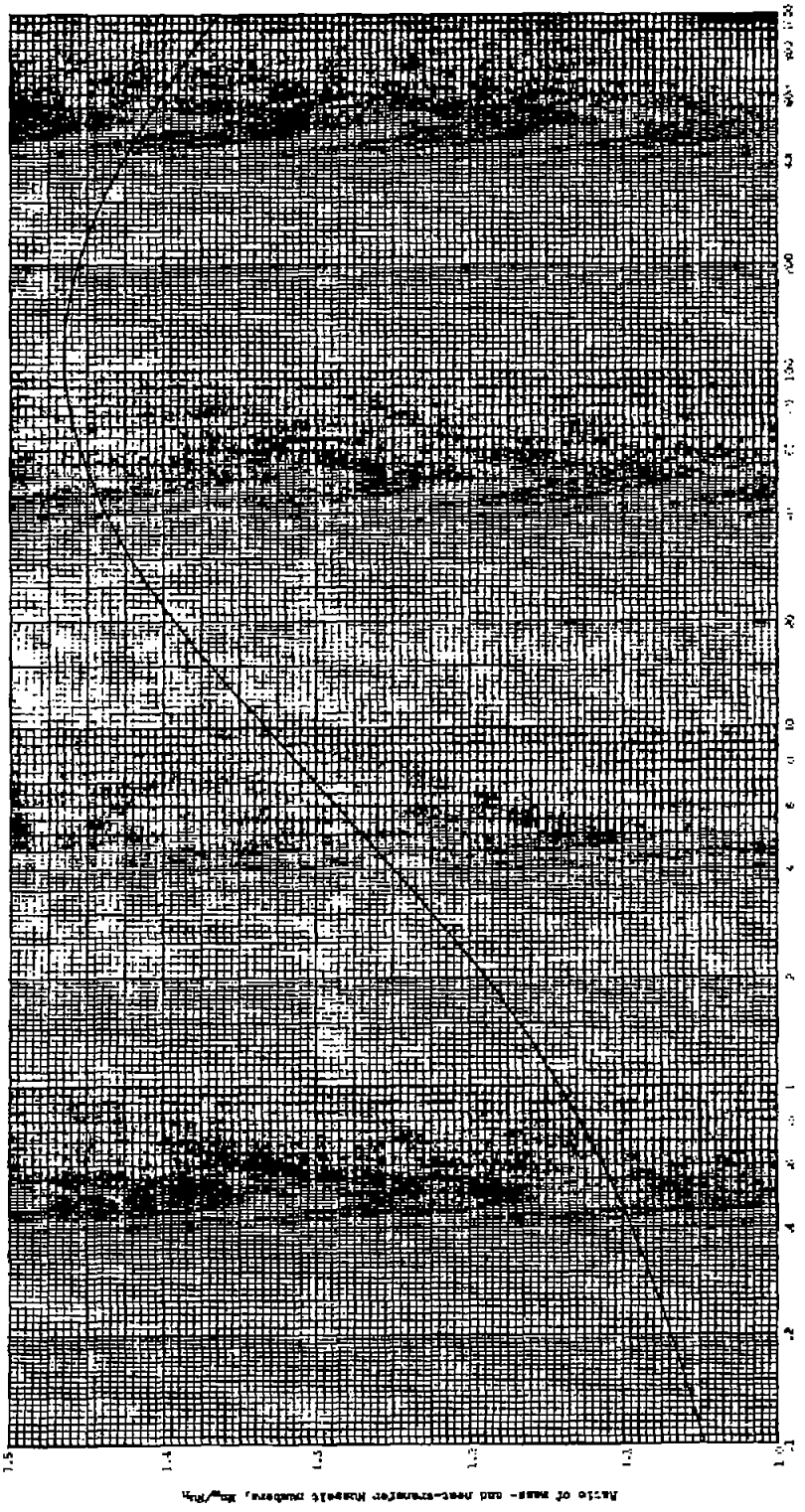

Figure 3. - Ratio of mass- and heat-transfer Nusselt numbers for cylinder spanning into normal air as function of Reynolds number.

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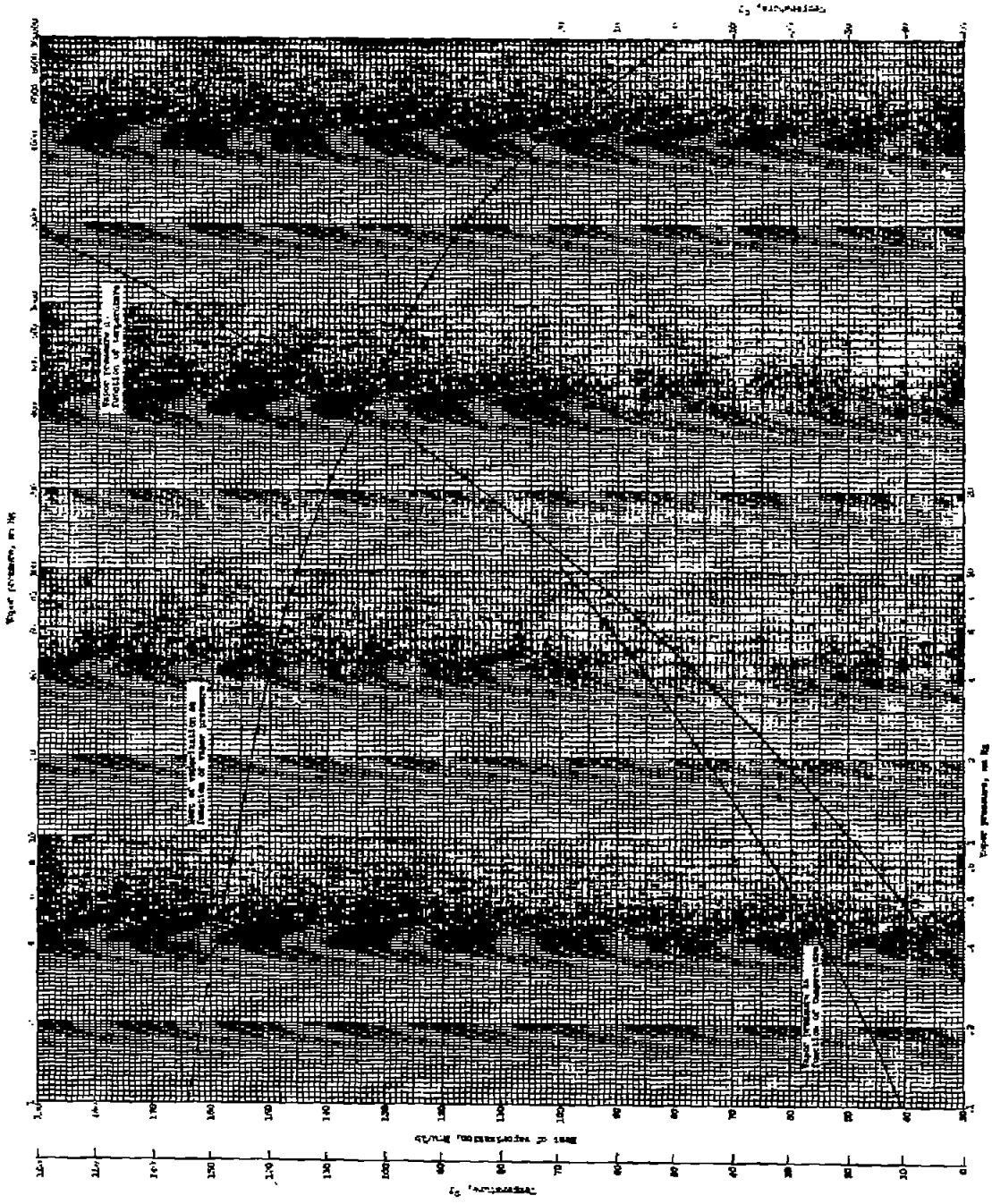

Figure 4. - Relations among temperature, vapor pressure, and heat of vaporization for gasoline.

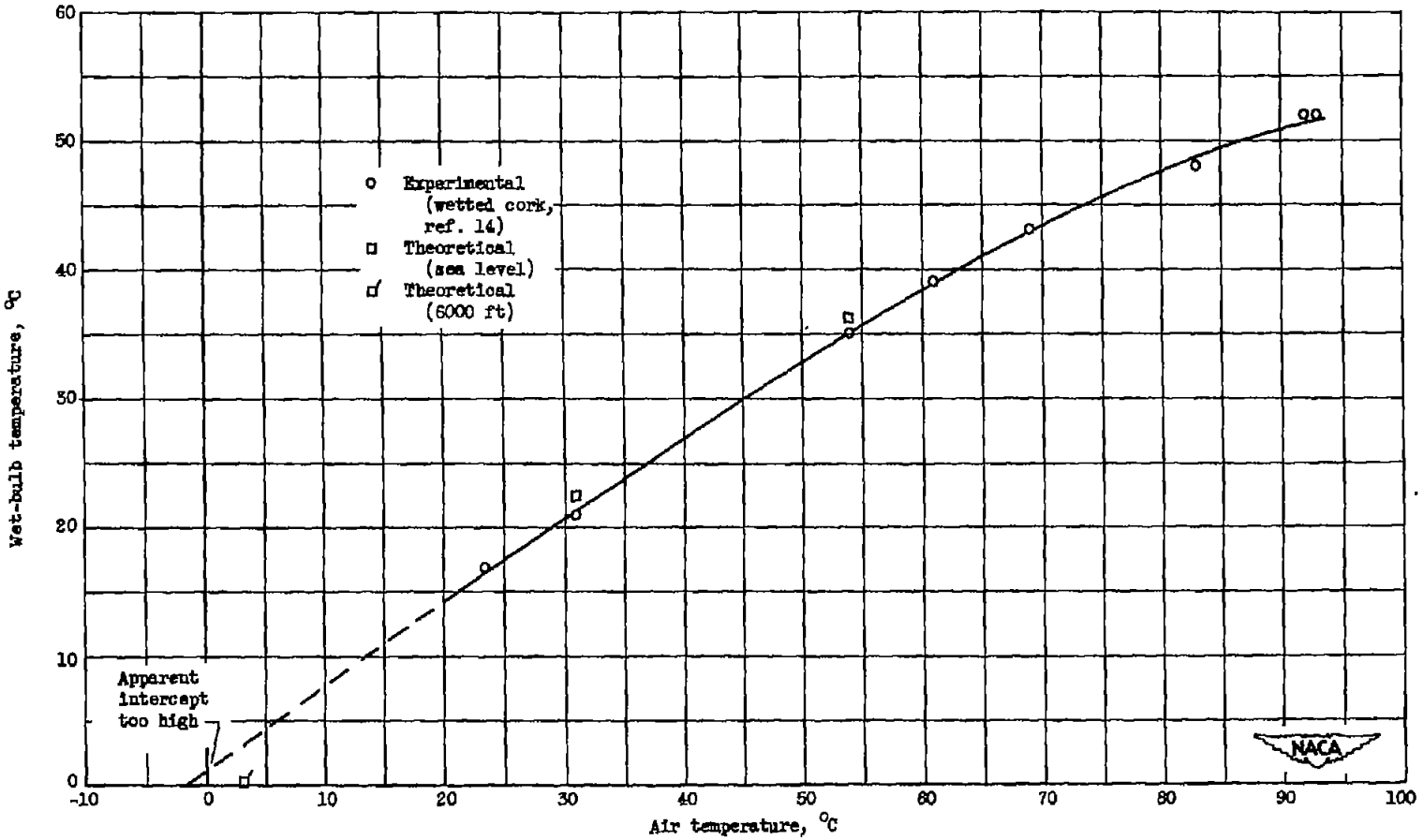

Figure 5. - Psychrometric behavior of n-octane spheres. Reynolds number equal approximately to 1000.

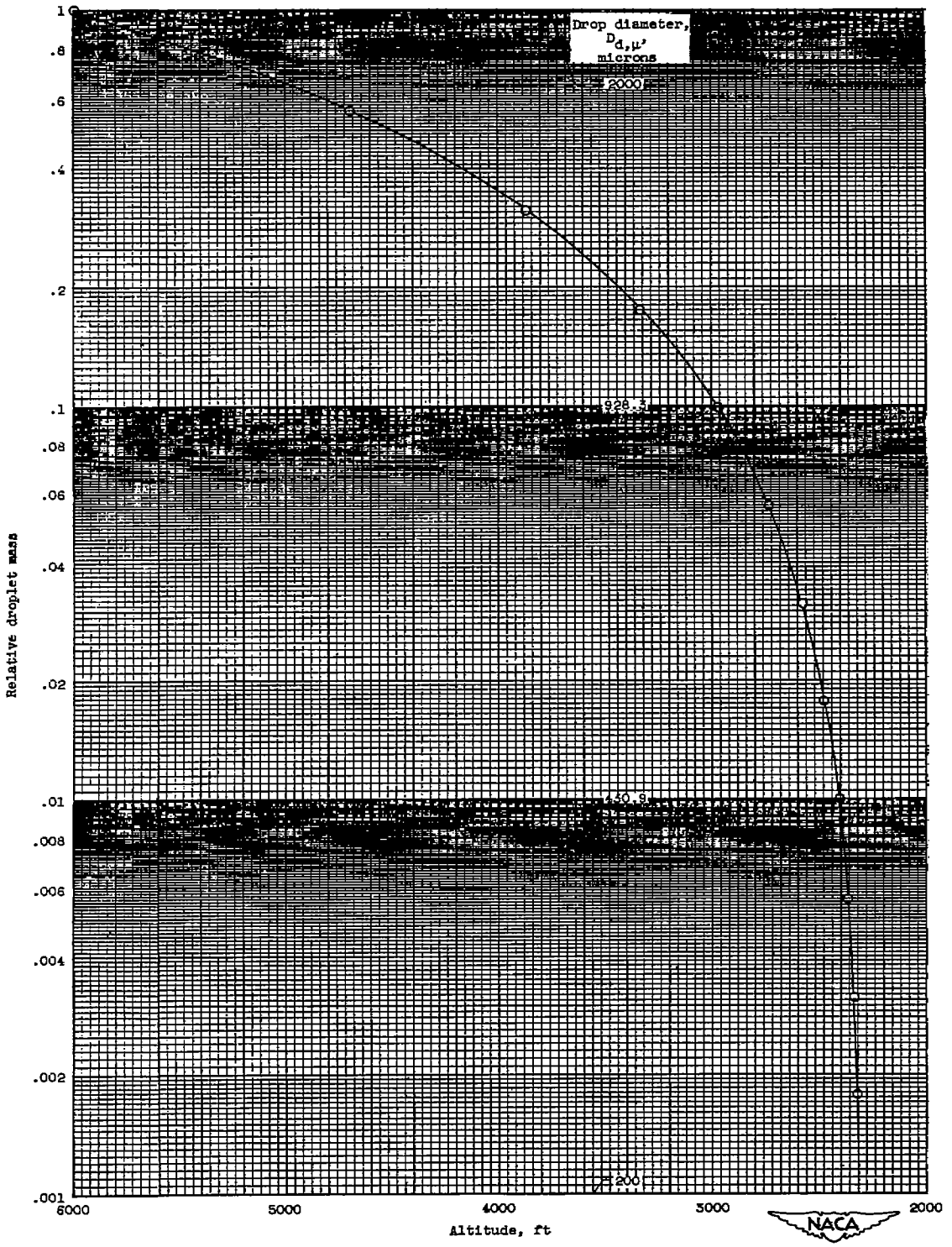

Figure 6. - Mass loss by evaporation of 2000-micron n-octane droplet falling through NACA standard atmosphere.

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